

BOUNDED LÜROTH EXPANSIONS: APPLYING SCHMIDT GAMES WHERE INFINITE DISTORTION EXISTS

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ABSTRACT. We show that the set of numbers with bounded Lüroth expansions (or bounded Lüroth series) is winning and strong winning. From either winning property, it immediately follows that the set is dense, has full Hausdorff dimension, and satisfies a countable intersection property. Our result matches the well-known analogous result for bounded continued fraction expansions or, equivalently, badly approximable numbers.

1. INTRODUCTION

In the fields of number theory and dynamical systems, a type of largeness of a set, that of being winning in the sense of Schmidt games, has quickly become important because fundamental sets in number theory—badly approximable numbers [9], badly approximable matrices [10]—and fundamental sets in dynamical systems—points with nondense orbits under C^2 -expanding circle maps [13], points with nondense orbits under linear automorphisms of the torus [1]—exhibit the winning property while not exhibiting the usual notion of largeness, namely that of being full Lebesgue measure. These sets are, moreover, null sets, but they do satisfy a countable intersection property and have full Hausdorff dimension, much like conull sets.

The main technique in this paper, the use of the notion of commensurate, is an advance in the application of the technique of Schmidt games to cases of infinite distortion, whereas previously only bounded distortion could be handled.¹ The technique in this paper, which handles this new, extra source of infinity, is a significant extension of the second-named author's work in [13] for some bounded distortion cases. We will borrow notation and ideas from [13]. Moreover, we intend our proof in this paper, which shows that the set of bounded Lüroth expansions is winning, to be a model for other cases which have infinite distortion, and such cases are plentiful and natural in number theory and dynamical systems.

1.1. Introduction to Lüroth expansions. Perhaps the simplest example of a case with infinite distortion is that of Lüroth expansions. These expansions are variants of the well-known continued fraction expansions and n -ary expansions where $n > 1$ is an integer. Like for these other expansions, every real number $x \in X := [0, 1]/0 \sim 1$ can be written as a finite or infinite series, called the *Lüroth expansion* or, equivalently, *Lüroth series* of x :

$$x = \frac{1}{a_1(x)} + \frac{1}{a_1(x)(a_1(x)-1)a_2(x)} + \cdots + \frac{1}{a_1(x)(a_1(x)-1) \cdots a_{n-1}(x)(a_{n-1}(x)-1)a_n(x)} + \cdots$$

where the natural number $a_k(x) \geq 2$ denotes the k -th digit for each integer $k \geq 1$. Also like for these other expansions, the digits of the Lüroth expansion for x are given by a dynamical

¹We defer the discussion of distortion to Section 6, especially Section 6.2.

system, namely $T : X \rightarrow X$ where

$$Tx = \begin{cases} n(n+1)x - n & \text{if } x \in [\frac{1}{n+1}, \frac{1}{n}), \\ 0 & \text{if } x = 0. \end{cases} \quad (1.1)$$

The first digit $a_1(x) = n + 1$ if $x \in [\frac{1}{n+1}, \frac{1}{n})$ for $n \geq 1$, and the k -th digit is obtained by iterating the dynamical system: $a_k(x) = a_1(T^{k-1}x)$ —when $T^{k-1}x = 0$ for a $k \geq 1$, there is no digit and we stop the iteration, obtaining a finite expansion.² A number x has *bounded Lüroth expansion* if there exists a natural number $N(x)$ such that $a_k(x) \leq N(x)$ for all $k \geq 1$, and, in particular, finite Lüroth expansions are bounded. We discuss properties of Lüroth expansions in Section 3. An introduction to Lüroth expansions and related number-theoretical objects can be found in a number of references, including a short monograph [3] by K. Dajani and C. Kraaikamp or another short monograph [6] by J. Galambos.

2. STATEMENT OF RESULTS

As a model proof for applying Schmidt games to cases of infinite distortion, we show³:

THEOREM 2.1. *The set of numbers with bounded Lüroth expansion is α -winning and α -strong winning for $\alpha := \frac{1}{8}$.*

Let T be the dynamical system in (1.1) that gives the digits of the Lüroth expansion. The theorem is equivalent (in a straightforward manner) to the following dynamical reinterpretation:

COROLLARY 2.2. *The set of points in X whose forward orbits under T miss an open interval with left endpoint 0 is α -winning and α -strong winning for $\alpha := \frac{1}{8}$.*

Now the intersection of any other (strong) winning set in \mathbb{R} (or X) with the set of bounded Lüroth expansions is also (strong) winning. Using results from [8, 1], one possible number-theoretic corollary is

COROLLARY 2.3. *The set of badly approximable numbers with bounded Lüroth expansion and bounded block n -ary expansion for every natural number $n > 1$ is winning and strong winning and thus is a dense set of full Hausdorff dimension.*

A real number x has *bounded block- k n -ary expansion* if there exists an $N(x) > 0$ such that every block of consecutive digits k has at most $N(x)$ digits, and the number x has *bounded block n -ary expansion* if it has bounded block- k n -ary expansion for all digits k . There is an obvious dynamical reinterpretation of the corollary, an interpretation which allows us to replace the number-theoretical concept of numbers having bounded block n -ary expansion with the natural (and more general) dynamical concept of numbers whose forward orbits (under $x \mapsto nx \bmod 1$) miss some neighborhood of a prescribed point.

Our Theorem 2.1 considerably strengthens the result of [11] (on the Hausdorff dimension of bounded Lüroth expansions) to the winning properties and allows us to obtain the above corollaries, which are not obtainable just from knowing the Hausdorff dimension. Furthermore, since the winning property is preserved by local isometries (see [9]) and the strong winning

²The number 0 has no Lüroth expansion according to our strict definition.

³Schmidt games and winning and strong winning sets are briefly discussed in Section 4; distortion, in Section 6.2.

property is preserved by quasisymmetric homeomorphisms (see [8]), these properties allow us to write corollaries similar to Corollary 1.2 of [12], corollaries which again are not obtainable just from knowing dimension.

3. PROPERTIES OF LÜROTH EXPANSIONS

The elementary properties of Lüroth expansions, we take from Chapter 2 of the monograph [3]. As typical with expansions such as these, we are only concerned with the numbers from the circle $X := [0, 1]/0 \sim 1$ because these expansions are defined modulo 1. In this section, a very important way of dealing with Lüroth expansions, the key concept of commensurate, will be introduced.

Let us first, however, introduce some notation. The absolute value of a set denotes the usual length or, equivalently, the probability Haar measure on X . The *Lüroth element (LE) of generation 0* is X . For $n \in \mathbb{N}$, a *Lüroth element (LE) of generation n* is a closed interval corresponding to the first n digits in a Lüroth expansion—this is the left-closed, right-open interval corresponding to all Lüroth expansions beginning with the given n digits union the right endpoint of this interval. We refer to these n digits as the Lüroth expansion corresponding to this LE. For $n \in \mathbb{N} \cup \{0\}$, let G_n denote the set of LEs of generation n . (Hence, $G_1 := \{[1/2, 1], [1/3, 1/2], \dots, [1/k + 1, 1/k], \dots\}$.)

Given these notions of Lüroth elements and generations, we observe the following properties:

- (1) Let $n \in \mathbb{N}$. Every element $E \in G_n$ has a unique left-adjacent element in G_n . We denote this element by E^- .
- (2) Let $n \in \mathbb{N}$. Every element $E \in G_n$ that does not correspond to a Lüroth expansion ending in the digit 2 has a unique right-adjacent element in G_n . We denote this element by E^+ .
- (3) Given $n \in \mathbb{N} \cup \{0\}$ and $E \in G_n$. Let U be any open set containing the left endpoint of E . Then $U \cap E$ contains infinitely many elements of G_{n+1} .
- (4) Given $n \in \mathbb{N} \cup \{0\}$ and $E \in G_n$. The only point of E satisfying the previous property is the left endpoint.
- (5) The maximum over all diameters of elements in G_n goes to zero as n goes to infinity.
- (6) Let $n \in \mathbb{N}$. For every $E \in G_n$ there exists a unique $F \in G_{n-1}$ such that $E \subset F$.
- (7) Let $n \in \mathbb{N} \cup \{0\}$. The interiors of any two distinct elements of G_n are disjoint.

Let $n \in \mathbb{N} \cup \{0\}$ and $E \in G_n$ be chosen. A point of E is an *accumulation point of E* if it satisfies the condition in Property (3). Thus the left endpoint of any LE is an accumulation point of that element. Property (4) says that it is the only one. An *accumulation point of generation n* is an accumulation point of some LE of generation n . Note that the intersection of the sets of accumulation points of distinct generations is empty. Also note that the right endpoint of E is an accumulation point of some generation less than or equal to n .

In the dynamical point of view, the accumulation points are the preimages of 0 under T . In particular, let E be an LE of generation n . Then the accumulation point belonging to E is a preimage of 0 under T^n , but not under T^{n-1} . And every such preimage is an accumulation point for an LE of generation n .

For us, a ball is assumed to have nonempty interior and it is usually assumed to be closed. Let $n \in \mathbb{N}$. A closed ball B is *commensurate with generation n (c.w.g n)* if B completely

contains an LE of generation n but no LE of generation $n - 1$. Since every ball is path-connected, it follows that B can contain at most one accumulation point of all generations up to (and including) $n - 1$.

REMARK 3.1. This notion of being commensurate—the essence of the proof of our main result—requires knowledge of both the length and position of B . It is possible for B to be arbitrarily small but commensurate with a small generation number. Such B s must be avoided if we are to play the Schmidt game.

The following lemma is easy to verify:

LEMMA 3.2. *For every closed ball B of X that is also a proper subset of X , there exists a unique $n \in \mathbb{N}$ such that B is c.w.g. n .*

The lemma has a corollary:

COROLLARY 3.3. *Any closed ball c.w.g. n (and also properly contained in X) is properly contained in at most two elements of G_{n-1} .*

Proof. The ball B is an interval and thus path-connected. Proper containment follows by the definition of commensurate. If B contains three elements of G_{n-1} , then pick an interior point from each of these elements. One of these points is closest to the left endpoint of B and another is closest to the right endpoint of B . The third point must lie between the other two. As these elements have pairwise disjoint interiors, every point of the third element (the one corresponding to the third point) lies in B , implying that B is not c.w.g. n , a contradiction. \square

Given an LE E , it is an element of some generation k and thus corresponds uniquely to a Lüroth expansion with digits a_1, \dots, a_k . Since our proof is an intricate and significant extension of the work of the second-named author in [13], we use some ideas and the notation from that paper: let $R_{a_1 \dots a_k} := E$ and $a_1 \dots a_k$ be referred to as a (finite) string in the letters $\mathbb{N} \setminus \{1\}$. For more on strings and the associated ideas from Markov partitions and symbolic dynamics, see Section 2 of [13] and Section 6.1 of this paper. The following lemma is easy to verify using elementary properties of Lüroth expansions:

LEMMA 3.4. *Given an integer $b \geq 2$ and an LE $R_{a_1 \dots a_k}$, we have*

$$\left| \bigcup_{a_{k+1} > b} R_{a_1 \dots a_k a_{k+1}} \right| = \frac{1}{b} |R_{a_1 \dots a_k}|.$$

4. SCHMIDT GAMES

In this section, we define Schmidt games and list their basic properties. W. Schmidt introduced the games which now bear his name in [9]. Let $0 < \alpha < 1$ and $0 < \beta < 1$. Let S be a subset of a complete metric space M and $\rho(\cdot)$ denote the radius of a closed ball. Two players, Player B and Player A , alternate choosing nested closed balls

$$B_1 \supset A_1 \supset B_2 \supset A_2 \dots$$

on M according to the following rules:

$$\rho(A_n) = \alpha \rho(B_n) \quad \text{and} \quad \rho(B_n) = \beta \rho(A_{n-1}). \quad (4.1)$$

The second player, Player A , *wins* if the intersection of these balls lies in S . A set S is called (α, β) -*winning* if Player A can always win for the given α and β . A set S is called α -*winning* if Player A can always win for the given α and every β . A set S is called *winning* if it is α -winning for some α . Schmidt games have three important properties for us [9]:

- An α -winning set in \mathbb{R}^n is dense and of full Hausdorff dimension.
- A countable intersection of α -winning sets is α -winning.
- An α -winning set in \mathbb{R}^n with a countable number of points removed is α -winning.

Recently, C. McMullen introduced a variant of these games in which the rules (4.1) are replaced by

$$\rho(A_n) \geq \alpha \rho(B_n) \quad \text{and} \quad \rho(B_n) \geq \beta \rho(A_{n-1}).$$

This variant results in *strong winning sets*, and the above properties for winning sets apply, *mutatis mutandis*, to strong winning sets in \mathbb{R}^n . Such strong winning sets are also winning and behave well under quasisymmetric homeomorphisms [8]. There have been other recent modifications to these games—see [7, 8, 2].

5. PROOF OF THE THEOREM

We give the proof for the winning property first and note that this proof also suffices for the strong winning property. Let $\alpha := 1/8$ and $0 < \beta < 1$ be arbitrary. Define $c_1 := 25$ and $b := \lceil \frac{2c_1}{\alpha\beta} \rceil$. We will specify a winning strategy for Player A . It is obvious that Player A can choose a ball that misses any given point of Player B 's current ball. Also, by playing the game for a finite number of rounds, Player A can force all subsequent choices of balls to be less to any given radius. Thus, without loss of generality, we may assume that B_1 does not contain the point 0 and has diameter strictly less than one. Hence B_1 is c.w.g. $g_1 \geq 1$.

Let $k := 1$. We claim that the ball B_k contains at most one accumulation point of generation $g_k - 1$. To see this claim, first note that the only way for B_k to contain an accumulation point of a generation strictly less than $g_k - 1$ is for the right endpoint of B_k to be this accumulation point (if B_k contains this accumulation point as some other point, then B_k must contain an LE of generation strictly less than g_k , a contradiction). If B_k contains two accumulation points of generations up to $g_k - 1$, then it must contain an LE of generation up to $g_k - 1$, a contradiction. Consequently, B_k contains at most one accumulation point of generations up to $g_k - 1$, and, if B_k does contain such an accumulation point and this accumulation point has generation strictly smaller than $g_k - 1$, then the right endpoint of B_k is the accumulation point.

If B_k contains an accumulation point, which we denote by p_k , of generations up to $g_k - 1$, then we denote

$$B_k^r := \{x \in B_k \mid x \geq p_k\}$$

$$B_k^\ell := \{x \in B_k \mid x \leq p_k\}.$$

For future choices of Player B 's balls (i.e. for integers $k > 1$), we make the analogous statements and definitions. We will also handle the case for which B_k contains no such accumulation point—see Case 3 below.

5.1. Initial step. We intend to use induction. For handling the initial step, let us define a ball $B_0 \supset B_1$ with radius $\frac{b}{c_1}\rho(B_1)$ —while we only care about the radius of B_0 , for definiteness, let B_0 have the same center as B_1 . There are three cases to consider:

Case 1: *The ball B_1 contains an accumulation point of generations up to $g_1 - 1$, and $|B_1^r| \geq |B_1^\ell|$.*

Let p_1 denote the accumulation point. Since it is not the right endpoint of B_1 , it must be (as shown above) of generation $g_1 - 1$. Let R_γ be the LE of the same generation as p_1 and having p_1 as left endpoint (therefore p_1 is the accumulation point of R_γ). Let q denote the left endpoint of R_{γ_2} and p_1^+ denote the accumulation point of generations up to $g_1 - 1$ immediately to the right of p_1 . Note that p_1^+ always exists because 0 is identified with 1 and 1 is a point to the right of all points in B_1 , a ball which, recall, does not contain 1. Then B_1^r is properly contained in the closed interval $[p_1, p_1^+]$.

Consider two subcases. First let B_1^r be properly contained in the interval $[p_1, q)$. It is now clear that Player A can choose A_1 to be contained in B_1^r and disjoint from the closed ball $\bar{B}(p_1, \frac{1}{b}\rho(B_0))$, the LE R_{γ_2} , and every element of $G_{g_1-1} \setminus \{R_\gamma\}$.

The other subcase is the case in which B_1^r is not properly contained in the interval $[p_1, q)$. By Lemma 3.4, it follows that $|B_1^r| \geq \frac{1}{2}|R_\gamma|$. Also, since B_1 is contained in the union of R_γ and its left-adjacent LE of the same generation (the left-adjacent LE always exists), then $2|R_\gamma| > |B_1|$ also follows by the same lemma. The conclusion of the previous paragraph is immediate.

Now B_2 is chosen. If B_2 is c.w.g g_1 , then Player A may choose any ball A_2 allowed by the Schmidt game. Player A can continue to play in this way for any B_k c.w.g. g_1 . We claim, however, that, at some iterate $n \geq 2$ of the game, B_n will be commensurate with a generation strictly greater than g_1 . The claim follows because, by choice of A_1 , A_1 can contain only a finite number of LEs of generation g_1 . If A_1 contains no such LE, then the claim follows for B_2 . If A_1 does contain such an LE, then it contains one of least length. Thus, for some iterate $n \geq 2$, B_n is too small to contain any such LE, which implies the claim.

Let $j_2 \in \mathbb{N}$ such that B_{j_2} is c.w.g g_1 and B_{1+j_2} is c.w.g. $g_2 > g_1$. By the above, $B_{1+j_2} \subset R_\gamma \setminus R_{\gamma_2}$. Form the set of LEs of the relevant generations that intersect B_{1+j_2} :

$$\mathcal{E} := \left\{ E \in \bigcup_{g=g_1}^{g_2-1} G_g \mid E \cap B_{1+j_2} \neq \emptyset \right\}.$$

Since B_{1+j_2} is c.w.g. g_2 , the ball is contained in at most two elements of G_{g_2-1} by Corollary 3.3. Therefore, every element in \mathcal{E} must contain one or the other element of generation $g_2 - 1$.⁴ We prove the following lemma, whose analogous version is also needed for the inductive step.

LEMMA 5.1. *The diameter of the ball B_{1+j_2} is larger than the diameter of any interval $(p, p + \frac{\sqrt{c_1}}{b}|E|)$ where $E \in \mathcal{E}$ and p is the accumulation point of E .*

⁴Even more, every element of \mathcal{E} not of generation $g_2 - 1$ must contain both (if there are two).

Proof. Since B_{1+j_2} is c.w.g. g_2 , there exists an element $E_{g_2} \in G_{g_2}$ such that $E_{g_2} \subset B_{1+j_2}$. Consequently, there exists a unique element $E_{g_2-1} \in G_{g_2-1}$ such that $E_{g_2} \subset E_{g_2-1}$. By recursion, we may define the chain of inclusions

$$E_{g_2} \subset E_{g_2-1} \subset \cdots \subset E_{g_1}$$

where $E_g \in G_g$.

Since $B_{1+j_2} \subset A_1$, we have that $E_{g_1} \cap A_1 \neq \emptyset$. By the choice of A_1 , the Lüroth expansion corresponding to E_{g_1} cannot end in the digit 2, which implies that both $E_{g_1}^+$ and $E_{g_1}^-$ exist.

Since $B_{1+j_2} \subset B_{j_2}$, we have that $E_{g_1} \cap B_{j_2} \neq \emptyset$. Since B_{j_2} is c.w.g. g_1 , B_{j_2} must completely contain (at least) one element of the set $\{E_{g_1}^-, E_{g_1}^+\}$.

Let \tilde{B}_{j_2} denote the closed ball with the same center as B_{j_2} , but with $\sqrt{c_1}$ times the radius. By an easy argument using Lemma 3.4, we have that $E_{g_1} \subset \tilde{B}_{j_2}$. Now note that $\sqrt{c_1}|B_{1+j_2}| \geq \sqrt{c_1} \frac{2c_1}{b} |B_{j_2}| \geq \frac{c_1}{b} |E_g|$ for $g_1 \leq g \leq g_2$, which implies the desired result. \square

COROLLARY 5.2. *Let $g_2 > g_1 + 1$. The ball B_{1+j_2} is disjoint from every interval $(p, p + \frac{1}{b}|E|)$ where E is an LE of generations from g_1 to $g_2 - 2$ and p is the accumulation point of E .*

Proof. Let F and F^- be the (possibly) two LEs of generation $g_2 - 1$ whose union contains (properly) B_{1+j_2} (by Corollary 3.3). Since F and F^- are adjacent LEs, they lie in the same LE of generation $g_2 - 2$ (if not, then B_{1+j_2} is not c.w.g. g_2 , which is a contradiction) and thus the same LE—call it F' —of whatever generation E is. There are two cases.

Case A: The LEs E and F' are distinct elements of the same generation.

The LEs E and F' can only intersect at an endpoint, which is an accumulation point of either E or F' . However, since B_{1+j_2} is contained in F' , it is disjoint from the interior of E , implying the desired result.

Case B: The LEs E and F' are the same element.

Assume that the conclusion does not hold. Let $E := R_\gamma$ for some string γ . Now by the elementary properties of Lüroth expansions ([3]), $|R_{\gamma b}| = \frac{1}{b(b-1)}|R_\gamma|$ —note that the LE $R_{\gamma b}$ is disjoint from $[p, p + \frac{1}{b}|E|)$ and $[p, p + \frac{1}{b-1}|E|) = [p, p + \frac{1}{b}|E|) \cup R_{\gamma b}$ by elementary Lüroth expansion properties (see also Lemma 3.4). Since p is the left endpoint of E and since B_{1+j_2} is contained in E , then the assumption implies that the left endpoint of B_{1+j_2} is contained in $[p, p + \frac{1}{b}|E|)$. Therefore, Lemma 5.1 implies that B_{1+j_2} contains $R_{\gamma b}$, an LE of generation at most $g_2 - 1$.

This contradicts the fact that B_{1+j_2} is c.w.g. g_2 . \square

If the interior of B_{1+j_2} contains an accumulation point q of generations up to $g_2 - 1$, then it must be of generation $g_2 - 1$ (otherwise, B_{1+j_2} is not c.w.g. g_2). Let E_q be the LE corresponding to q . Let q^- be the accumulation point of E_q^- . Then the only two intervals that Player A must avoid and may (possibly) intersect B_{1+j_2} are $(q^-, q^- + \frac{1}{b}|E_q^-|)$ and $(q, q + \frac{1}{b}|E_q|)$. If the interior of B_{1+j_2} does not contain an accumulation point of generations up to $g_2 - 1$, then B_{1+j_2} lies completely in some

$E_q \in G_{g_2-1}$ where q is the corresponding accumulation point—and the one interval that Player A must avoid is $(q, q + \frac{1}{b}|E_q|)$. In either case, Lemma 5.1 implies that B_{1+j_2} is at least $\sqrt{c_1}/2$ times larger than the (union of) interval(s) Player A must avoid, and the corollary implies that if $g_2 > g_1 + 1$, then B_{1+j_2} automatically avoids any intervals $(p, p + \frac{1}{b}|E|)$ where $E \in \bigcup_{g=g_1}^{g_2-2} G_g$.

Case 2: *The ball B_1 contains an accumulation point of generations up to $g_1 - 1$, and $|B_1^r| < |B_1^\ell|$.*

Let p_1 denote the accumulation point. Since B_1 is c.w.g g_1 , B_1^ℓ is properly contained in an element $R_\gamma \in G_{g_1-1}$ by Corollary 3.3. Then p_1 is the right endpoint of R_γ . Player A chooses A_1 to be the closed ball with right endpoint p_1 . Since $|B_1^\ell| < |R_\gamma|$ and α is small enough, $A_1 \subset R_{\gamma_2}$ and, moreover, if p is the accumulation point of R_{γ_2} , then A_1 is disjoint from $[p, p + \frac{1}{b}|R_{\gamma_2}|)$. Therefore, A_1 is disjoint from all intervals $(p, p + \frac{1}{b}|E|)$ where p is an accumulation point of generations up to g_1 and E is the LE corresponding to p .

Now B_2 is chosen. By the choice of A_1 , A_1 is c.w.g $g > g_1$, and, even more precisely, $R_{\gamma_2\tilde{\gamma}} \subset A_1 \subset R_{\gamma_2\tilde{\gamma}}$ where $\tilde{\gamma}$ is a string of $g - g_1 - 1$ repeating digits 2. Thus, we have that $|A_1| > |R_{\gamma_2\tilde{\gamma}}| = \frac{1}{2}|R_{\gamma_2\tilde{\gamma}}|$ by Lemma 3.4. Let B_2 be c.w.g g_2 —hence $g_2 \geq g$. If $g_2 = g$, then B_2 is contained in $E := R_{\gamma_2\tilde{\gamma}}$, an LE of generation $g_2 - 1$. If $g_2 > g$, then, by Corollary 3.3, B_2 must be contained in at most two adjacent LE of generation $g_2 - 1$ both of which lie in $R_{\gamma_2\tilde{\gamma}}$; denote these two elements by E^- and E .

Thus, for $g_2 \geq g$, we have $|E^-| < |E| \leq |R_{\gamma_2\tilde{\gamma}}|$. Consequently, $|B_2| \geq \frac{2c_1}{\alpha b}|A_1| \geq \frac{c_1}{\alpha b}|R_{\gamma_2\tilde{\gamma}}|$, which is much larger than the (at most two) interval(s)—namely, $[q^-, q^- + \frac{1}{b}|E^-|)$ and $[q, q + \frac{1}{b}|E|)$ where q^- and q are the accumulation points of E^- and E , respectively—that Player A must avoid.

LEMMA 5.3. *Let $g_2 > g_1 + 1$. The ball B_2 is disjoint from every interval $(p, p + \frac{1}{b}|F|)$ where F is an LE of generations from g_1 to $g_2 - 2$ and p is the accumulation point of F .*

Proof. Since E and E^- are adjacent LEs of generation $g_2 - 1$, they lie in the same LE of generation $g_2 - 2$ and thus the same LE—call it E' —of whatever generation F is. There are two cases.

Case A: The LEs F and E' are distinct elements of the same generation.

The proof is analogous to the proof of Case A of Corollary 5.2.

Case B: The LEs F and E' are the same element.

There are two subcases to consider. The first is when F is of generations g_1 to $g - 2$ (provided that $g > g_1 + 1$; otherwise, this subcase is not needed). Since $A_1 \subset R_{\gamma_2\tilde{\gamma}}$ where $\tilde{\gamma}$ is a string of $g - g_1 - 1$ repeating digits 2, the result is clear from the elementary properties of Lüroth expansions and the size of b .

The second subcase is when F is of generations $g - 1$ to $g_2 - 2$. Assume that the conclusion does not hold. The condition of this case, Case B, implies that $F \subset R_{\gamma_2\tilde{\gamma}}$. Let θ be the (possibly empty) string such that $F = R_{\gamma_2\tilde{\gamma}\theta}$ and p be the left endpoint of F . Thus $|R_{\gamma_2\tilde{\gamma}\theta b}| = \frac{1}{b(b-1)}|R_{\gamma_2\tilde{\gamma}\theta}|$ —note that the LE $R_{\gamma_2\tilde{\gamma}\theta b}$ is disjoint from $[p, p + \frac{1}{b}|F|)$ and $[p, p + \frac{1}{b-1}|F|] = [p, p + \frac{1}{b}|F|) \cup R_{\gamma_2\tilde{\gamma}\theta b}$. Since p is the left endpoint of F and since B_2 is contained in F , then the assumption implies

that the left endpoint of B_2 is contained in $[p, p + \frac{1}{b}|F|)$. Since $|B_2| \geq \frac{2c_1}{ab}|A_1| \geq \frac{c_1}{ab}|R_{\gamma 2\bar{\gamma}}| \geq \frac{c_1}{ab}|F|$, we have that B_2 contains $R_{\gamma 2\bar{\gamma}\theta b}$, an LE of generation at most $g_2 - 1$. This contradicts the fact that B_2 is c.w.g. g_2 . \square

Let $j_2 = 1$; then, we conclude as in Case 1.

Case 3: *The ball B_1 does not contain an accumulation point of generations up to $g_1 - 1$.*

The given condition on B_1 implies that it is completely contained in the interior of an LE E of generation $g_1 - 1$. Now since B_1 is c.w.g. g_1 , it completely contains an LE of generation g_1 —if it were to contain such an element with last digit 2, it would contain an accumulation point of generations up to $g_1 - 1$, a contradiction. Therefore, it contains an LE of generation g_1 with last digit not 2.

Let p_1 be the accumulation point corresponding to E . And let p_1^+ be the accumulation point of generations up to $g_1 - 1$ which is also the right endpoint of E .

Setting $E = R_\gamma$ and treating B_1 as we did B_1^r in Case 1, we handle this case exactly as Case 1, except for the following. Recall the definition of q from Case 1. The first subcase is handled exactly as in Case 1. The second subcase—in which B_1 is not properly contained in the interval $[p_1, q)$ —is handled as follows. Since B_1 is c.w.g. g_1 , it cannot be properly contained in $R_{\gamma 2}$. Therefore, the condition of this subcase implies that B_1 contains q . Whence, it must contain $R_{\gamma 3}$ because it is c.w.g. g_1 and it cannot contain $R_{\gamma 2}$. Therefore, B_1 is large relative to R_γ (more precisely, it is at least $1/6$ the length of R_γ) and it is clear that A_1 can be chosen to be disjoint from the closed ball $\bar{B}(p_1, \frac{1}{b}\rho(B_0))$, the LE $R_{\gamma 2}$, and every element of $G_{g_1-1} \setminus \{R_\gamma\}$. The remainder of this case (Case 3) is handled exactly as the remainder of Case 1.

This completes the three cases and the initial step of the induction.

5.2. Induction step. Our induction index is n . Let $j_1 := 1$. Let $J_n := \sum_{i=1}^n j_i$. By the induction hypothesis, B_{J_n} is c.w.g. $g_n > g_{n-1}$; therefore, there exists (by Corollary 3.3), either two LEs E and E^- of generation $g_n - 1$ such that $B_{J_n} \subset E^- \cup E$ or one LE E of generation $g_n - 1$ such that $B_{J_n} \subset E$. If $g_n > g_1 + 1$, then, also by the induction hypothesis, B_{J_n} avoids $(q, q + \frac{1}{b}|F|)$ where q is an accumulation point of generations g_1 up to $g_n - 2$ and F is the LE corresponding to q . Finally, again by the induction hypothesis, $|B_{J_n}|$ is (at least) $\sqrt{c_1}/2$ times larger than $|(p^-, p^- + \frac{1}{b}|E^-|) \cup (p, p + \frac{1}{b}|E|)|$ where p is the accumulation point of E and p^- is the accumulation point of E^- .

Thus, it is possible for Player A to chose A_{J_n} to be disjoint from all $(p, p + \frac{1}{b}|E|)$ where E is an LE of generation $g_n - 1$ and p is the accumulation point of E . We choose A_{J_n} , which will be so disjoint, by considering three cases:

Case 1: *The ball B_{J_n} contains an accumulation point of generations up to $g_n - 1$, and $|B_{J_n}^r| \geq |B_{J_n}^\ell|$.*

This case is handled in the analogous way to Case 1 of the initial step—except B_1 is replaced by B_{J_n} , A_1 is replaced by A_{J_n} , B_2 is replaced by B_{J_n+1} , and so on. Also, the two subcases give similar conclusions as in the inductive step, except A_{J_n} is disjoint from $(p_n, p_n + \frac{1}{b}|R_\gamma|)$ and the LE $R_{\gamma 2}$ (recall that p_n must be an accumulation point of generation $g_n - 1$ for this case). The rest of this case is analogous to the initial step.

Case 2: *The ball B_{J_n} contains an accumulation point of generations up to $g_n - 1$, and $|B_{J_n}^r| < |B_{J_n}^\ell|$.*

This case is handled in the analogous way to Case 2 of the initial step—except B_1 is replaced by B_{J_n} , A_1 is replaced by A_{J_n} , B_2 is replaced by B_{J_n+1} , and so on.

Case 3: *The ball B_{J_n} does not contain an accumulation point of generations up to $g_n - 1$.*

This case is handled in the analogous way to Case 3 of the initial step—except B_1 is replaced by B_{J_n} , A_1 is replaced by A_{J_n} , B_2 is replaced by B_{J_n+1} , and so on. (Note that, as in Case 1 of the induction step, the two subcases follow easily. For the first subcase, consider as in Case 1 of the induction step; for the second subcase, consider as in Case 3 of the initial step.)

This completes the induction.

5.3. Finishing the proof for winning. Let $x \in X$. If E is an LE, let p_E be the accumulation point of E . The induction above shows that the set

$$BL(b) := \left\{ x \in X \mid \text{there exists an } n(x) \in \mathbb{N} \text{ such that} \right. \\ \left. x \notin \bigcup_{m \geq n} \bigcup_{E \in G_m} (p_E, p_E + \frac{1}{b}|E|) \text{ and there exists } c(x) > 0 \text{ such that} \right. \\ \left. x \notin \bigcup_{m=0}^{n-1} \bigcup_{E \in G_m} (p_E, p_E + c|E|) \right\}$$

is (α, β) -winning. (Note that a given point x lies in at most two LEs of the same generation. Therefore, for a fixed $n(x) \in \mathbb{N}$, x lies in either $n + 1$ or $n + 2$ LEs of generations up to n .) Consequently, the set $BL := \bigcup_{a \geq b} BL(b)$ is α -winning.

Now let $x \in BL$. Then $x \notin \bigcup_{m \geq 0} \bigcup_{E \in G_m} (p_E, p_E + \tilde{c}|E|)$ where $\tilde{c} := \min\{c, \frac{1}{a}\}$. Thus, BL is contained in the set of numbers with bounded Lüroth expansion. And the proof of the theorem for α -winning is complete.

Finally, note that accumulation points have two Lüroth expansions (using a slightly less strict algorithm than the one given in Section 1). One expansion is finite and the other has trailing digits 2—in either case, bounded. Removing all accumulation points from BL , however, still results in an α -winning set.

5.4. Proof for strong winning. Recall that we must find a winning strategy for Player A . Therefore, we may and do constrain Player A 's choices of radius size to be always equal to α times the radius of Player B 's current ball. With this constraint, the proceeding proof, without change, shows that BL is α -strong winning.

6. CONCLUSION

In this section, we compare the result in this paper to the second-named author's result in [13], discuss infinite versus bounded distortion, and suggest further applications of the technique in this paper.

6.1. Infinite versus finite element Markov partitions. To distinguish between the result in this paper and the work in Section 5 of [13], it helps to consider strings and their associated Markov partitions. The basic idea is that the strings encode the motion of the associated dynamical system (in our case the Lüroth map T), and this encoding is established using Markov partitions. In our case, the collection of Lüroth elements in G_1 is a natural choice for a Markov partition associated with T . In particular, G_1 satisfies the definition of a Markov partition for T as stated in Section 2.1 of [13]—except that the cardinality of G_1 is not finite, but infinite. Note also that the definition of R_α for a (finite) string α and properties (2.6 – 2.13) of [13] also hold for G_1 . (For completeness, the transition matrix for our T is an infinite matrix of all 1’s in the letters $\mathbb{N} \setminus \{1\}$.) Hence, G_1 is an example of an infinite element Markov partition, while the Markov partitions in [13] are the usual (finite element) Markov partitions.

But, although G_1 is an infinite element Markov partition, it is, perhaps, the simplest example. It and its associated Lüroth expansions are the infinite element analog of n -ary expansions where $n > 1$ is an integer. In this latter case, we can take the simplest Markov partition of $\{[0, \frac{1}{n}], \dots, [\frac{n-1}{n}, 1]\}$. If, further, we only ask to miss an open neighborhood with 0 as the left endpoint, then the proof in [13] greatly simplifies: the difficulty in this proof is in dealing with missing a neighborhood of an arbitrary point and in dealing with the nonlinearity of the dynamical system.⁵ Moreover, missing a neighborhood of 0 for the n -ary expansion was already shown by Schmidt in 1966 [9].

6.2. Infinite versus bounded distortion. What is different between this infinite element Markov partition and the usual finite element Markov partitions is distortion. In particular, finite element Markov partitions have bounded distortion in that, over a fixed, finite window of generations, the ratio of length (or other relevant measure) of the element with largest length to smallest length is finite (and this finite bound depends only on the size of the window). Explicitly, finite element Markov partitions satisfy Lemma 2.2 of [13], while our infinite element Markov partition clearly does not, even if the window is the smallest that it can be, namely over the same generation.⁶ Thus, our dynamical system has *infinite distortion*, while the ones considered in [13] have bounded distortion. And this difference does not allow us to port the proofs in [13], even in the simplest case of missing an open neighborhood with left endpoint 0—the infinite distortion, which manifests itself in our notion of accumulation points for the Lüroth expansion, is a new source of infinity and a new source of difficulties. But, the infinite distortion is also a new source of solutions in that, the accumulation points, which manifest the infinite distortion, are also used, via the proofs of Lemma 5.1 and Corollary 5.2, to our advantage because these points can be distinguished from non-accumulation points via the geometry of the expansion and the notion of commensurate.

6.3. Further applications. We intend the proof in this paper to be a model for applying Schmidt games to cases where infinite distortion exist. These cases naturally occur in number theory and dynamical systems, especially in other types of expansions. Many further applications are possible.

⁵As far as the authors’ know, the nonlinear case of this type of result in higher dimensions is still open.

⁶It seems appropriate to refer to this property as *infinite distortion*, while leaving *unbounded distortion* for the case where, as one slides the fixed window toward infinity, the bound on distortion grows to infinity.

We mention one such application. The continued fraction expansion is the most natural expansion because it leads to notions of best approximations—the applications of continued fractions are far-reaching and important. Like its variant the Lüroth expansion, the digits of the continued fraction expansion are generated by a dynamical system, in this case the well-known Gauss map, which is a system where infinite distortion exists, much like our map T . Applying our proof technique, but modifying it to handle the fact that accumulation points for the Gauss map alternate between left and right endpoints of the “Gauss elements” for odd and even generation numbers, should lead to another proof that the set of real numbers with bounded continued fraction expansion or, equivalently, the set of badly approximable numbers is winning. The two known proofs are based on the repulsion of the elements of a Farey sequence for fixed denominators [9], which is a number-theoretic proof, and bounded orbits under the geodesic flow in the space of unimodular lattices [4], which is a dynamical proof. The proof involving the flow, however, is not the most elementary dynamical proof because the geodesic flow can be regarded as a suspension of the Gauss map and thus is not the dynamical system which defines the continued fraction expansion, but an induced system. A proof adapting our technique in this paper would just involve the Gauss map and be an elementary dynamical proof.

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BOUNDED LÜROTH EXPANSIONS: APPLYING SCHMIDT GAMES WHERE INFINITE DISTORTION EXISTS

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